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The benefits of ethanol use for hydrogen production in urban transportation

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ABSTRACT

The purpose of this paper is to describe the benefits of sugar cane ethanol in Brazil, appointing the productivity of this type of fuel based on hectares of plantation, its carbon dioxide cycle and the contribution to reduce the greenhouse effect. In the following step the uses of ethanol for hydrogen production by steam reforming is analyzed and some comparison with natural gas steam reforming is performed. The sugar cane industry in Brazil, in a near future, in the hydrogen era, could be modified according to our purpose, since besides the production of sugar, and ethylic and anhydric alcohol, Brazilian sugar cane industry will also be able to produce biohydrogen.

Fuel cells appear like a promising technology for energy generation. Among several technologies in the present, the PEMFC (proton exchange membrane fuel cell) is the most appropriate for vehicles application, because it combines durability, high power density, high efficiency, good response and it works at relatively low temperatures. Besides that it is easy to turn it on and off and it is able to support present vibration in vehicles. A PEMFC's problem is the need of noble catalysts like platinum. Another problem is that CO needs to be in low concentration, requiring a more clean hydrogen to avoid fuel cell deterioration.

One part of this paper was developed in Stockholm, where there are some buses within the CUTE (clean urban transport for Europe) project that has been in operation with FC since January 2004. Another part was developed in Guaratinguetá, Brazil. Brazil intends to start up a program of FC buses. As conclusion, this paper shows the economical analysis comparing buses moved by fuel cells using hydrogen by different kinds of production. Electrolyze with wind turbine, natural gas steam reforming and ethanol steam reforming.

Contents

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Nomenclature

C	fuel cost (US$/kW h)
C_f	part of operation in urban transport cost (US$/km h)
C_{fc1}	urban transport cost with FC systems (US$/km h)
C_{inv}	part of investment in urban transport cost (US$/km h)
C_{main}	part of maintenance in urban transport cost (US$/km h)
C_{fc2}	urban transport cost with FC systems (US$/kW h)
CUTE	clean urban transport for Europe
f	annuity factor (1/year)
FC	fuel cell
H	equivalent period of operation (h/year)
I	investment cost (US$/kW)
ICE	internal combustion engine
k	payback period (year)
LHV	lower heat value (kJ/kg)
$\dot{m}$	mass flow (kg/s)
r	annual interest rate (%)
W	power electric engine (kW)
Greek letters	
ΔS	useful life of the bus (km)
η	FC or ICE efficiency (%)

1. Introduction

The criteria that influence the evolution of the world energy sector in the present century are complex. Both are typical objectives such as safety in supply and exploration of resources, competitiveness of companies, and the necessity to preserve the environment (locally and globally) through the use of new technologies and sustainable use of existing resources. In the energy field, an important cause of pollutant, emissions is linked to the increase of transportation, as seen on many publications [1–5]. In fact, nearly one-quarter of the world's energy is utilized in the transportation sector [6]. In the last 40 years, some economic, social and cultural changes (increase of productivity, free time availability, decentralized urban development, etc.) have encouraged a wide diffusion of vehicles. The World Health Organization (WHO) estimates that urban air pollution causes 800,000 premature deaths each year. Fossil fuels burned by internal combustion engines of vehicles contribute in 90% of urban air pollution, including lead, carbon monoxide, ozone and particulates [7].

The global warming is caused mainly by burning of fossil fuels (oil, diesel, gasoline, etc.) that emit millions of tons of pollutants. Besides, the certainty that those fossil fuels are non-renewable resources allows more researches in cleaner energy, and particularly for vehicles. In this way, fuel cell (FC) has a special attention because it can be applied in urban transport and improves the actual environmental situation.

Among several technologies in the present, FC appears like a promising technology alternative for energy generation, principally in substitution of internal combustion engine and thus is considered for transportation purposes (automotive, marine and aerospace). FC is very efficient system consisting of an electrochemistry process rather than combustion. Specifically, water, electricity, and heat are generated through the combination of hydrogen and oxygen. The development of FC technology includes the project of low resistance membranes, highly diffusive electrodes, and reduced use of noble metal catalysts [8].

In Brazil, São Paulo Metropolitan Region (SPMR), composed by 39 municipalities and with a population of 18 million, diesel buses are one of the major contributors to the air pollution. This situation is doing Brazil to start up a program of environmental regulation applied for the public transport. The Ministry of Mines and Energy (MME), together with São Paulo Metropolitan Urban Transport Company (EMTU/SP), the United Nations Development Program (PNUD), the Global Environmental Facility (GEF) and the Financing Agency of Studies and Projects (FINEP) is moving forward with the Environmental Energy Strategy: Buses with Hydrogen Fuel Cell Project [9].

In Europe, nine cities have been participated in the CUTE project (Amsterdam, Barcelona, Hamburg, London, Luxembourg, Madrid, Porto, Stockholm and Stuttgart). Three buses have been operated for 24 months in each one of these cities. The first bus started to operate in 2003. In Stockholm the CUTE project was coordinated by Stockholm Public Transport (SL), and Fortum—The energy and gas distributor company. KTH (the Royal Institute of Technology) made the initial studies [10].

2. Ethanol

Ethanol is a volatile, flammable, colorless liquid that has a strong characteristic odor. The physical properties of ethanol stem were primarily from the presence of its hydroxyl group and the shortness of its carbon chain. Ethanol is a versatile solvent, miscible with water and with many organic solvents.

Two unusual phenomena are associated with mixtures of ethanol and water. Ethanol–water mixtures have less volume than the sum of their individual components. Mixing equal volumes of ethanol and water results in only 1.92 volumes of mixture. The addition of even a few percent of ethanol to water sharply reduces the surface tension of water.

Mixtures of ethanol and water that contain more than about 50% ethanol are flammable and easily ignited. Ethanol–water solutions that contain less than 50% ethanol may also be flammable if the solution is first heated.

Ethanol fuel (ethyl alcohol) is the same type of alcohol found in alcoholic beverages. It can be utilized as a fuel, mainly as a biofuel alternative to gasoline, and is widely utilized in cars in Brazil. Because it is easy to manufacture and process, and can be made from very usual crops such as sugar cane and maize (corn), it is an increasingly usual alternative to gasoline in some countries of the world.

Brazil has the largest and most successful biofuel programs in the world, involving production of ethanol from sugar cane, and it has the world's first sustainable biofuels economy. In 2006 Brazilian ethanol provided around 20% of the country's road transport sector fuel consumption needs, and more than 40% of fuel consumption for the light vehicle fleet. Together, Brazil and the United States lead the industrial world in global ethanol

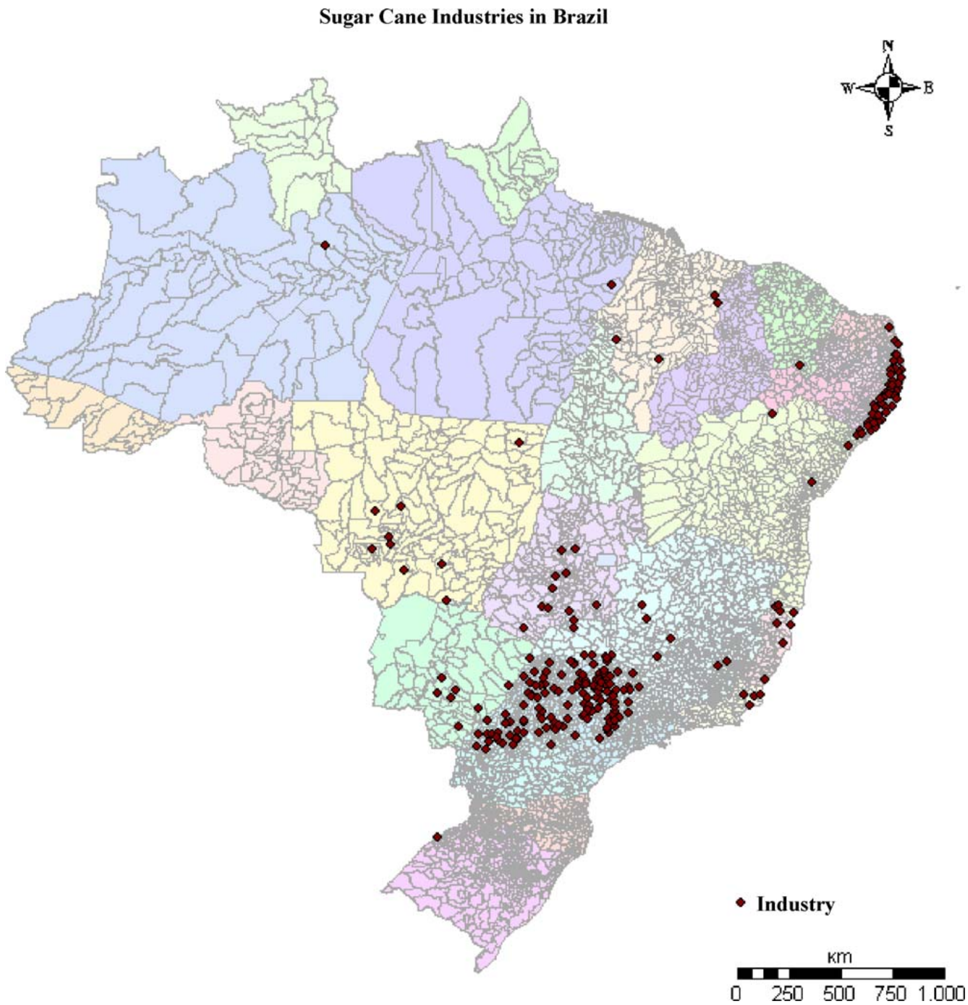

Fig. 1. Sugar cane industry in Brazil [12].

production, accounting together for 70% of the world's production and nearly 90% of ethanol as fuel [11].

Moreover, Brazil has an extensive ethanol distribution grid. Fig. 1 shows the distribution of sugar cane industry. The major concentration of sugar industry is basically near of plantation. The highest concentration of the sugar cane industry is located in northeast and southeast, because of the favorite climate conditions [12].

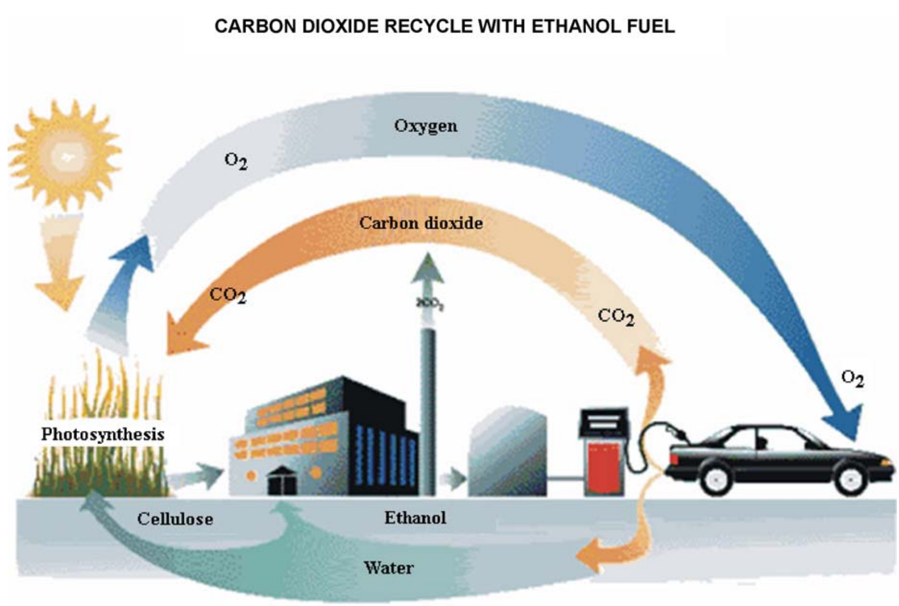

Fig. 2. Carbon dioxide recycle with ethanol fuel [14].

Fig. 3. Total carbon dioxide emission for 1000 liters Brazilian ethanol [15].

Grunwald [13] in his article published in *Time Magazine, "The Clean Energy Myth"*, did some good comments about the sugar cane ethanol Brazilian situation and did bad comments about corn ethanol from United States (USA). Brazil's sugar cane-based industry is far more efficient than the corn-based industry from USA. Brazilian distillers are able to produce ethanol with a production cost of about 0.22 US$ per liter, compared with the 0.30 US$ per liter for corn-based ethanol. USA corn-based ethanol costs 30% more because the corn starch must first be converted to sugar before being distilled into alcohol. In the Brazilian case, the total area utilized for sugar cane plantation is about 1% (3.6 million hectares) while in the case of the USA, the corn plantation is about 3.7% (10 million hectares). In the other side, the productivity of the Brazilian ethanol (from sugar cane) is about 7500 liters per hectare, while the productivity of the ethanol from USA (from corn) is about 4000 liters per hectare.

Brazilian ethanol allows the carbon cycle, decreasing the environmental problems as greenhouse effect (GHG) about 90%, while the USA ethanol decreases about 30% [14].

Figs. 2 and 3 show information about the greenhouse effect. In Fig. 2, it was depicted that plantation of sugar cane emits oxygen and consumes carbon dioxide by photosynthesis process.

In Fig. 3 is shown the ethanol cycle production. Observe that a cycle, since the preparation of the soil, until to arrive to consumer, per each 1000 liters of ethanol, 309 kg of carbon dioxide is emitted. If compared to a cycle of gasoline, since the extraction of oil until it arrives to consumer, gasoline cycle emits 3368 kg of carbon dioxide to atmosphere, the result proves the difference between both the process is 3059 kg more emissions to gasoline cycle, appointing the greater advantage for sugar cane based ethanol [15].

In the near future, in the hydrogen era, the sugar cane industry of Brazil could be modified according to our purpose, as shown in Fig. 4. In this case, in addition to the production of sugar and ethanol, the Brazilian sugar cane industry will be able to produce biohydrogen.

3. Hydrogen

Hydrogen is the simplest, lightest and most plentiful element in the universe. It is made up of one proton and one electron revolving around the proton. In its normal gaseous state, hydrogen is colorless, odorless, tasteless, non-toxic and burns invisibly (in the case of air mixture). It should not be considered a "fuel", but instead, should be considered as an energy transport mechanism.

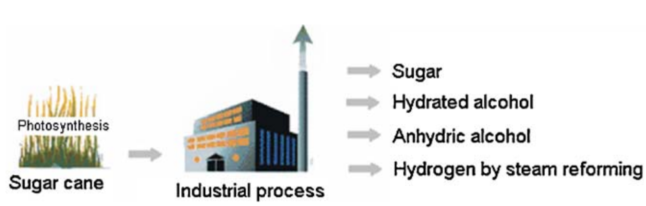

Fig. 4. New schematic of sugar cane industry in Brazil in hydrogen era.

Currently, most hydrogen is made from natural gas through a process known as reforming. Reforming separates hydrogen from hydrocarbons by adding heat. Hydrogen can also be produced from a variety of sources including water and biomass [16].

3.1. Some processes of hydrogen production

3.1.1. The electrolysis process

In the water electrolysis process the hydrogen is produced by electrochemically splitting water molecules (H_2O) into their constituents hydrogen (H_2) and oxygen (O_2). The decomposition of water takes place in a so-called electrolysis cell and consists of two partial reactions that take place at two electrodes. The electrodes are placed in an ion-conducting electrolyte (usually an aqueous alkaline solution with 30% potassium hydroxide—KOH). Gaseous hydrogen is produced at the negative electrode (cathode) and oxygen at the positive electrode (anode). The necessary exchange of charge occurs through the flow of OH-ions in the electrolyte and current (electrons) in the electric circuit. In order to prevent a mixing of the product gases, the two reaction areas are separated by a gas-tight, ion-conducting diaphragm membrane. Energy for the water splitting is supplied in the form of electricity [17].

To achieve the desired production capacity, numerous cells are connected in series forming a module. Larger systems can be assembled by adding up several modules. Two types of electrolyzers are typical: atmospheric and pressurized units. An advantage of the atmospheric electrolyzer, working at ambient pressure, is its lower energy consumption but the required space for the unit is relatively high. Pressurized electrolyzers deliver hydrogen up to 30 bar. This reduces energy demand for compression and may even make compressor stages redundant. Today, atmospheric electrolyzers with capacities of up to 500 Nm^3/h and pressurized units with a capacity range of 1–120 Nm^3/h are standard products [17].

3.1.2. The steam reformer process

The process is divided into the generation of a hydrogen-rich reformate stream by means of steam methane reforming (SMR) and the following hydrogen purification by means of pressure swing adsorption (PSA). The process route consists mainly of [17].

3.1.2.1. Pre-treatment of the feed. The hydrocarbon feedstock is desulphurised using, e.g., activated carbon filters, pressurized and, depending on the reformer design, either preheated and mixed with process steam or directly injected with water into the reformer without the need of an external heat exchanger. The fresh water is first softened and demineralized by an ion-exchange water conditioning system. One option is high pressure reforming with integrated heat exchangers and a working pressure of up to 16 bar which reduces the geometric volume of the reformer vessels and is ideal for a downstream treatment by means of PSA or compression. The other option is to operate the reformer at low pressures (1.5 bar) with an increased conversion ratio and compress the syngas prior to purification [17].

3.1.2.2. Steam reforming of natural gas. Methane and steam are converted within the compact reformer furnace at approximately 900 °C in the presence of a nickel catalyst to a hydrogen rich syngas stream according to the following reactions [17]:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad (1)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (2)$$

The heat required for reaction (1) is obtained by the combustion of fuel gas and purge/tail gas from the PSA system. Following the reforming step the synthesis gas is fed into the CO conversion reactor to produce additional hydrogen. Heat recovery for feed-stock preheating takes place at different points within the process chain to optimize the energy efficiency of the reformer system (depending on the reformer design). This process can be utilized to reforming of the natural gas, biogas, ethanol, etc.

In the case of ethanol steam reforming, the details will be shown in the item 5.

3.1.2.3. Gas purification-PSA-system. Hydrogen purification is achieved by means of pressure swing adsorption (PSA). The PSA unit consists of four vessels filled with selected adsorbents. The PSA reaches hydrogen purities higher than 99.999% by volume and CO impurities of less than 1 vppm (volumetric part per million) fulfilling the specifications set by the fuel cell bus supplier. Pure hydrogen from the PSA unit is sent to the hydrogen compressor, while the PSA off-gas from recovering of the adsorbents, called tail gas, is fed to the reformer burner. Depending on the reformer design, a recuperative burner is utilized featuring high efficiency and low nitrogen oxide (NO_X) emissions. During normal operation, the burner can be operated solely on the tail gas stream [17].

3.2. Storage

Because hydrogen is such a light gas, it is difficult to store a large amount in a small space. That is a challenge for auto engineers, who want to match, 300-mile vehicle range, but some recent vehicles have done it. Researchers are examining an impressive array of storage options, with U.S. Department of Energy (DOE) support. Today's prototype FCVs use compressed hydrogen tanks or liquid hydrogen tanks. New technologies such as metal hydrides and chemical hydrides may become viable in the future. Another option would be to store hydrogen compounds – methanol, gasoline, ethanol or other compounds – on board, and extract the hydrogen when the vehicle is operating [18].

3.3. Delivery

Since fuel cell convert hydrogen into electricity, the main question on everybody's mind is "Where and how am I going to get

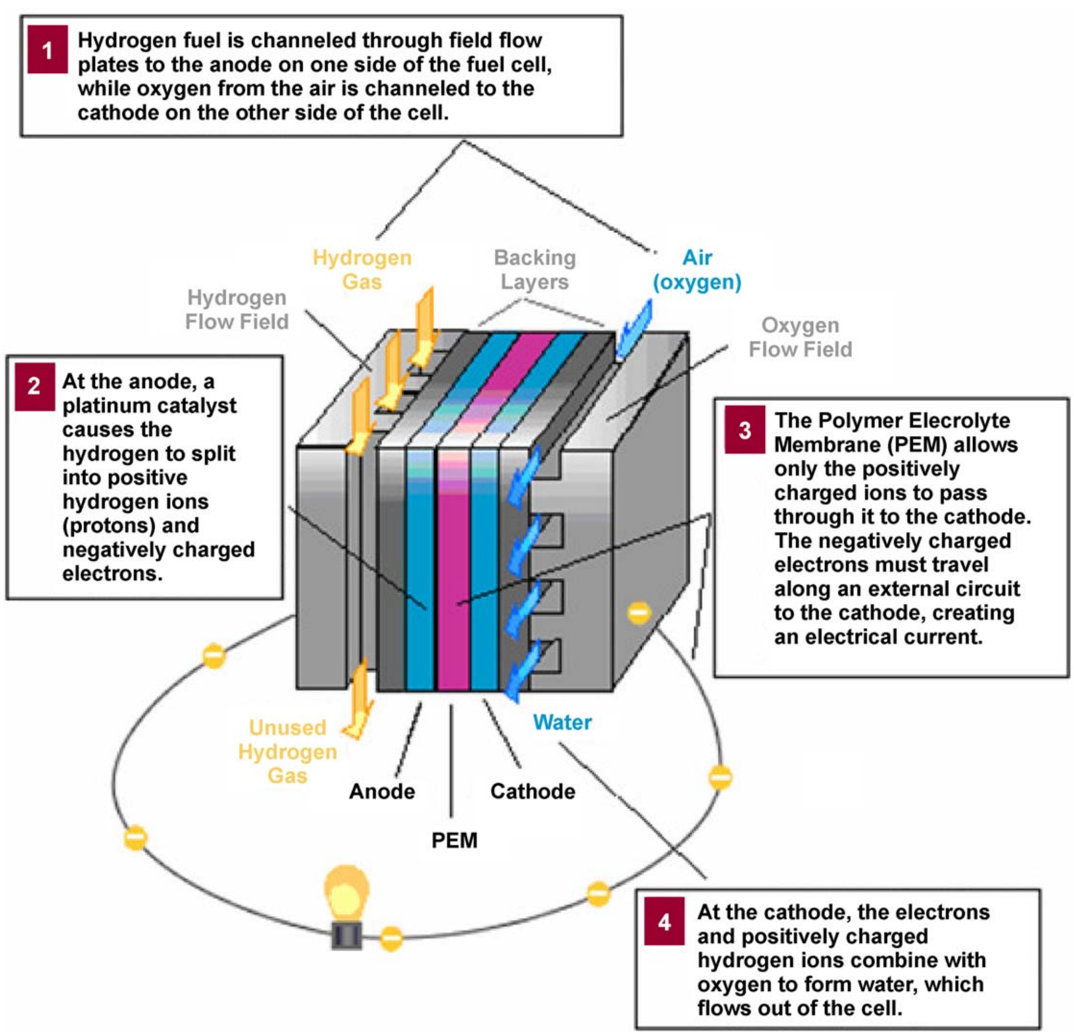

Fig. 5. Proton exchange membrane fuel cell [23].

the hydrogen to fuel up my fuel cell car?'' If auto engineers choose to store hydrogen compounds on board the vehicle, tomorrow's fuel infrastructure would look a lot like today's. Many other options are being explored to deliver hydrogen to fuel cell vehicles (FCVs) [18]:

Centralized production and delivery: Hydrogen production and delivery services including a limited pipeline system already serve the needs of today's industrial demand.
On-site production: The energy station of the future might produce hydrogen on demand from natural gas, other compounds or even water.
Innovative approaches: Fuel cell products that generate electrical power sometimes come with hydrogen generators called reformers or steam reformers. An energy station might purchase one of these units, use the electricity for operations and tap into the reformer to produce hydrogen for vehicles.

The ultimate solution might be solar or wind or hydroelectric powered hydrogen filling stations, where electricity generated is utilized to extract hydrogen from water. Two solar stations already are operating in Southern California for the hydrogen production.

4. How fuel cell work

There are several types of fuel cell, but PEMFC is typically utilized in automobiles. This device uses hydrogen and oxygen from the air to produce electricity. Arrangements must be made for the removal of products resulted from the chemical reactions. Ideally, electrodes and electrolyte remain invariant, the overall process being the consumption of fuel and oxidant with the resulting release of electrical energy, as showed in other papers [19–22]. Fig. 5 shows how FC works.

Most of fuel cells designed for use in vehicles produce electricity containing less than 1.16 V—far from enough to power a vehicle. Therefore, multiple cells must be assembled into a fuel cell stack.

The power generated by a fuel cell stack depends on the kind and the number of individual fuel cells that comprise the stack and the surface area of the PEMFC [23].

5. Ethanol steam reforming

For hydrogen production, several technologies may be studied. Steam reforming is one of the most usual technologies installed in chemical industries. The reforming efficiency is obtained through studying of physical–chemical properties of feedstock, thermodynamic conditions (temperature and pressure of reaction, technical configurations of reformer such as dimensions and catalysts, and feedstock and water flows). The method to be utilized depends on the suggested fuel cell, which will use the reforming products. The fuel cell technology determines hydrogen purity and other reforming product rates. Steam reforming occurs in the presence of a catalyst, the syngas produced includes hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), among others. Some arrangements to minimize some reactions that can contribute to decrease the hydrogen production are necessary. Since this reaction is endothermic, heat from external sources is necessary. To minimize losses, some products of the steam reforming such as non-reacted fraction of reactants might be utilized to heat reactants burning them through after-burners [24].

5.1. Reforming reactions

Souza et al. [25] indicated that this way of reforming can be described through the following reactions, which are the main ones:

- *Global reaction*: Ethanol reacts with water, both in gaseous state in a endothermic reaction, occurring the production of carbon dioxide and hydrogen, as shown in Eq. (3):

$$C_2H_5OH + 3H_2O \rightarrow 2CO_2 + 6H_2 \tag{3}$$

  Fig. 6 shows inlet and outlet flows of ethanol steam reforming process, and Fig. 7 shows the prototypes developed in São Paulo State University, by Energetic Systems Optimization Group (www.feg.unesp.br/gose).
- *Steam reforming reaction*: Eq. (4) shows this reaction where the production of carbon monoxide and hydrogen occurs:

$$C_2H_5OH + H_2O \rightarrow 2CO + 4H_2 \tag{4}$$

- *Water gas shift reaction*: Since carbon monoxide damages fuel cell catalyst, an additional process is necessary to remove it. The water gas shift reaction (see Eq. (5)), is exothermic, reversible, and occurs at lower temperatures than the former reaction:

$$CO + H_2O \rightarrow CO_2 + H_2 \tag{5}$$

- *Methanation*: Several chemical reactions can occur simultaneously. Eq. (6) shows methane production from carbon monoxide:

$$CO + 3H_2 \rightarrow CH_4 + H_2O \tag{6}$$

- *Bouduard reaction*: This reaction (see Eq. (7)) describes carbon production from carbon monoxide decomposition:

$$2CO \rightarrow CO_2 + C \tag{7}$$

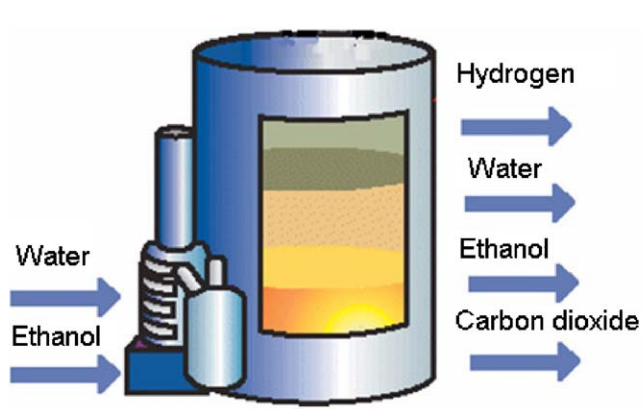

Fig. 6. Steam reforming of ethanol process.

Fig. 7. Prototypes developed by authors [26].

6. Interest in the use of a FC in buses for urban transport

A ground transport vehicle that seems particularly interesting for adoption of a fuel cell is the bus for urban transport. It is possible also for another kind of transports and another application. The main reasons for use in buses are [6]:

- The dimensions and structure of the bus allow installation of fuel cells and their auxiliaries, including the hydrogen tanks (if it were stored in gaseous form on the bus). The weight percentage increase would represent a lower problem compared with private cars.
- The ratio between the engine power and the weight of the vehicle is low: a bus of 18 tons with a medium speed of 70 km/h has a power of 150 kW.
- The bus circulates in the center of the urban areas where the air pollution is serious.

In these areas, a zero emission vehicle could gain high revenue in terms of social costs connected with air pollution, with an important benefit of public opinion and of administrators.

- A FC technology is, at present, much more expensive than traditional engines. Buses are bought and managed in fleets of a large number of units, and this allows an investment and maintenance cost reduction. Moreover, if the refueling structure were very expensive for a single vehicle, it would decrease in case of utilization of a fleet of 100 buses.
- The urban transport service is usually managed by a public administration, which is more interested in the acquisition of social benefits and which is less bound by short term revenue of the investment.
- Some characteristics of a fuel cell engine are particularly interesting for a bus: the engine is not noisy, vibrations are absent and the electric engine has a smooth operation, causing an increase in comfort of the users.

7. The CUTE project and hydrogen fuel cell buses in Stockholm

The clean urban transport for Europe (CUTE) project is the largest demonstration project of fuel cells and hydrogen today. In nine European cities, both hydrogen-powered fuel cell buses and hydrogen infrastructure were tested and demonstrated during two years [26].

Demonstration projects such as the CUTE project is a way to have the public meet and become familiarized with the technology. In fact, there is an explicit goal of the CUTE project to make hydrogen and fuel cell technology visible through the use of the fuel cell buses [26].

The buses in the CUTE project, all in all 27 buses, were operated for more than a year and the results of several studies within the project are emerging. In Stockholm, the buses were at first operated on a special demonstration route; the "Water route" in downtown Stockholm, and this introduction attracted much attention in the media. After eight months of operation, the buses were put in service on an ordinary bus route, route 66, also in downtown Stockholm [26].

The fuel cell buses are based on a conventional bus platform, the 12 m Mercedes-Benz Citaro low-floor city bus. In the fuel cell version of the bus, the internal combustion engine (ICE) has been replaced by a central electric motor, which powers a standard automatic gearbox. Similar to the configuration of the conventional bus, all the bus' auxiliaries in the fuel cell bus are powered mechanically. A special feature of the fuel cell bus however is that the auxiliaries are powered by the central electric motor via a special additional gearbox on the rear end of the motor. The fuel cell system and the hydrogen storage are located on the roof of the bus for both space and safety reasons. The general bus layout is shown in Fig. 8.

A driver opinion poll regarding technical and environmental aspects of the fuel cell buses project in comparison to conventional diesel buses, presented in Fig. 9, was performed. The responses were very positive.

8. Urban buses moved by fuel cells in Brazil

The project urban buses moved by fuel cells in Brazil was developed by Ministry of Mines and Energy (MME) e by Metropolitan Company of Urban Buses (EMTU/SP). There is a partnership with the United Nations Development Program (UNDP), Global Environment Facility (GEF) and Research and Projects Financing (FINEP). This technology guarantees zero emissions and as a result allows to develop a cleaner solution to public urban transport in Brazil [9].

The EMTU/SP is responsible for this project in Brazil, and are keeping this program of minimization of emissions from public urban vehicles. In this way, researches in energy area are developed, which includes tests involving usage of ethanol and natural gas, hybrid buses, and now buses utilizing hydrogen.

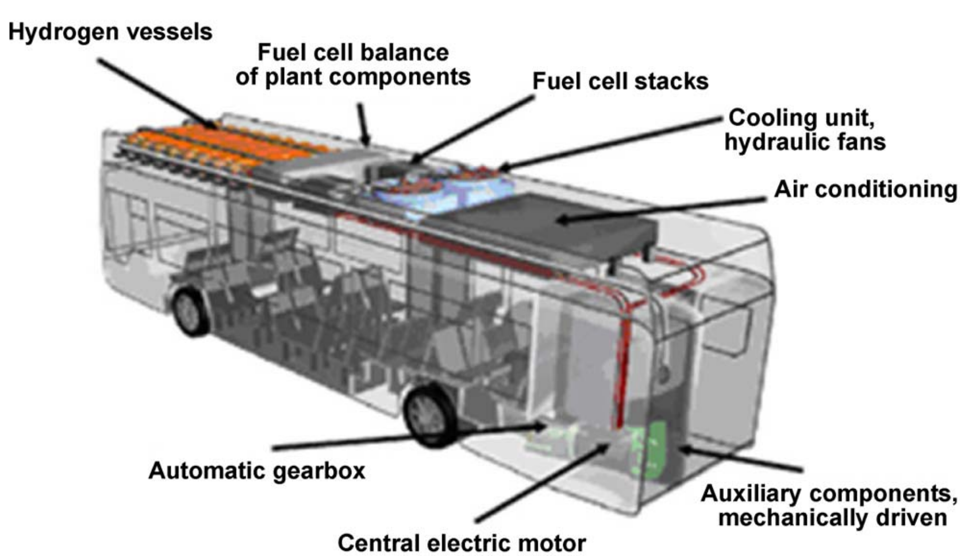

Fig. 8. The Mercedes–Benz's fuel-cell-powered bus Citaro [27].

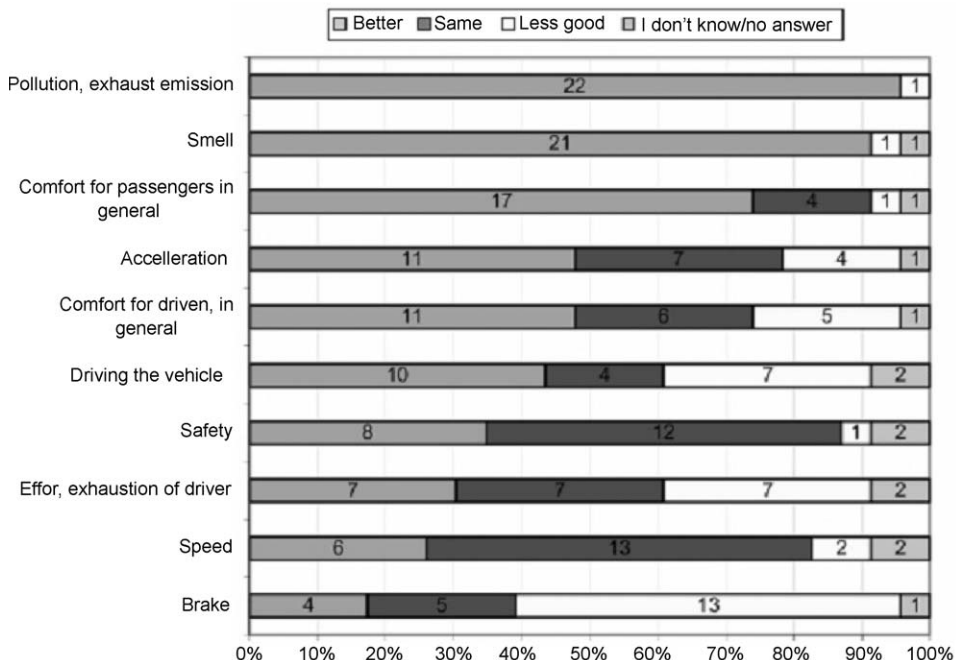

Fig. 9. Summarized results from the bus driver survey in CUTE Stockholm, November 2004, after 11 months of operation of the fuel cell buses. Note that the number of respondents varies for different questions [26].

The first Brazilian urban bus moved by fuel cell, as showed in Fig. 10, is 12 m long, contains 3 doors, air conditioning system, has capacity to attend 63 passengers, and can ride up 300 km (utilizing 15 kg of hydrogen to each 100 km). This type of vehicle will be utilized in the metropolitan region of São Paulo, where a large amount of pollutants are commonly detected [9].

9. Economic analysis

This section compares economically buses moved by fuel cells, using hydrogen produced by different kinds of processes: Electrolyze by wind turbine, natural gas steam reforming and Brazilian ethanol steam reforming, according to the price report by Department of Energy (DOE) in USA [28] (with inflation correction), considering large facilities (plants of hydrogen production with cost estimated to 2010) around 1.34–25.4 million Nm^3/day. Based on the methodology of Souza et al. [25] and Torres [29] the cost of hydrogen production by steam reforming of ethanol was determined, considering a medium facility (7200 Nm^3/day).

Fig. 10. The Brazilian urban bus [9].

The cost of hydrogen production by these processes of production is showed in Fig. 11 and the calculations were based on the methodology developed by Silveira et al. [30].

For the calculation of urban transportation cost (C_{fc}) using fuel cell for buses, the following considerations are utilized. The medium cost of hydrogen production was utilized, according to Fig. 11. The cost of hydrogen production through electrolysis is 0.225 US$/m^3 (0.07600 US$/kW h), using natural gas steam reforming is 0.12 US$/m^3 (0.04054 US$/kW h) and using ethanol steam reforming is 0.08 US$/m^3 (0.02702 US$/kW h). Environmental aspects in the costs of hydrogen in FC buses were not considered, but the emissions of dioxide carbon by steam reforming of natural gas is about 10 times higher than steam reforming of ethanol, considering the process of extraction of natural gas.

The investment cost of fuel cell will decrease in some years, with technological evolution and increase of production volume of units. Many authors have indicated values for the investment in

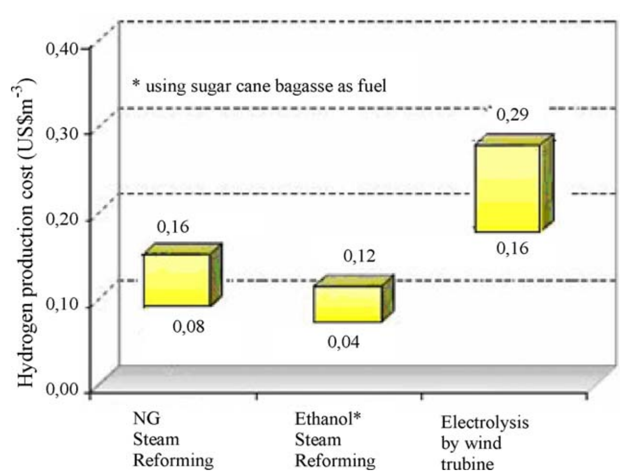

Fig. 11. Comparative cost of hydrogen production.

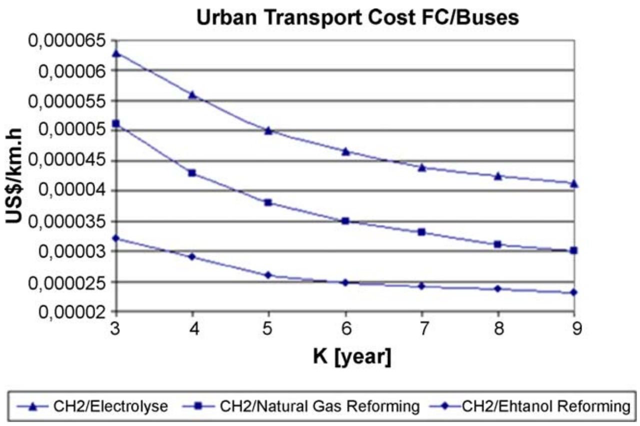

Fig. 12. Urban transport cost to FC buses (US$/km h).

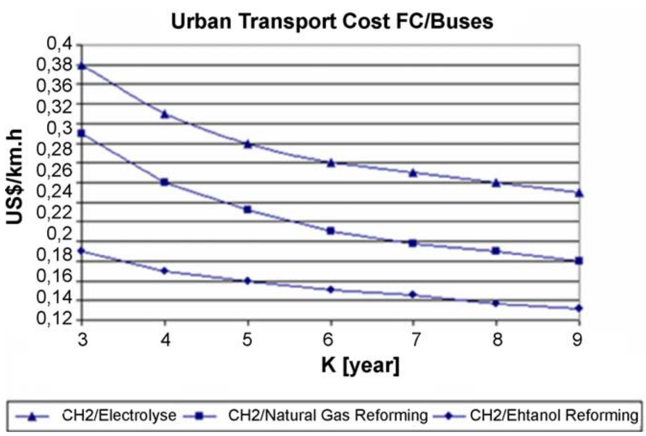

Fig. 13. Urban transport cost to FC buses (US$/kW h).

fuel cell. Torres [29], Doty [31] and Neto [32], appointed investment costs for PEMFC between US$ 2000/kW and US$ 3000/kW. In this paper is considered a medium investment cost (I_{fc}) of US$ 2500/kW.

Other parameters that were considered: η_{fc} = 48% (efficiency of fuel cell); W = 250 kW (power electric); LHV = 119,742.48 kJ/kg (lower heat value); ΔS = 1,500,000 km (useful life of the bus), H = 4800 h/year (equivalent period of operation—considering 16 h per day in 300 days). The utilized equations were cited below:

$$\dot{m} = \frac{w}{\eta \times \mathrm{LHV}} \times 100 \tag{8}$$

$$q = 1 + \frac{r}{100} \tag{9}$$

$$f = \frac{q^k \times (q-1)}{q^k - 1} \tag{10}$$

$$C_{inv} = \frac{I \times f \times w}{H \times \Delta S} \tag{11}$$

$$C_f = \frac{C \times LHV \times \dot{m}}{\Delta S} \tag{12}$$

$$C_{main} = 0.1 \times C_{inv} \tag{13}$$

The global equation for the urban transport cost is

$$C_{fc1} = \left(\frac{I_{fc} \times f \times w}{H \times \Delta S}\right) + \left(\frac{c_{H_2} \times \mathrm{LHV} \times \dot{m}}{\Delta S}\right) + 0.1\left(\frac{I_{fc} \times f \times w}{H \times \Delta S}\right) \tag{14}$$

$$C_{fc2} = \left(\frac{I_{fc} \times f}{H}\right) + \left(\frac{c_{H_2} \times LHV \times \dot{m}}{w}\right) + 0.1\left(\frac{I_{fc} \times f}{H}\right) \tag{15}$$

The results are showed in Figs. 12 and 13.

It is possible to observe that for 4800 h/year, the FC bus becomes more economically viable using hydrogen produced by ethanol steam reforming. The level of pollutant emissions of bus moved with hydrogen by electrolysis of wind turbine is lower than via steam reforming. However in Brazil, there is no wind enough in every place to installation of wind turbine and this device is very expensive.

In the case of hydrogen produced by steam reforming, ethanol is the best, either in economical aspects or in the control of pollutant emissions.

10. Conclusions

This paper shows the fuel cell as a good alternative to urban transport, promoting environmental and life quality.

Comparing with ICE buses, the FC buses have many advantages:

- Combustion process is not necessary, consisting in a direct energy conversion, decreasing pollutants emissions.
- Gasoline engines have efficiency between 13% and 25%, diesel engines, between 30% and 35%, and fuel cells have global efficiency of about 48%.
- The ICE could be substituted easily by an electric motor, electric motor is smaller, the vehicle gain internal space.
- Transmission systems are not necessary, seeing that the push-on and brake systems are controlled by carrying-on electric devices, could decrease operation, maintenance and fuel consuming costs.
- As the push-on and brake are controlled by electric system, the vehicle is noiseless.

Urban buses were focused because public transportation is responsible for a great part of pollutants emissions and by the fact to be possible settle fuel cells in fleets and to put into practice easily.

The hydrogen, the principal energy carrier to fuel cells, can be produced through various ways, but ethanol steam reforming is the best way to guarantee the volume of production necessary in the Brazilian case. The integration or association of hydrogen production with sugar industry, certainly, can put Brazil in a good classification in the "Hydrogen Era", in the near future. When hydrogen is produced by water electrolyzers, pollutants are not emitted, but great amount of energy is necessary, and that is what becomes the process expensive. On the other hand, in the case of surplus of energy from hydroelectric power plants, the production of this type of hydrogen could be one feasible alternative.

However, as showed in this economic analysis, at the present time the fuel cell technology is not viable, but in the medium-term, fuel cell buses will become competitive compared to internal combustion engine. Breaking down some barriers and start a market with sufficient scale is necessary to justify the investments in further development of fuel cell and in the scaling-up of production, which will bring this technology to acceptable levels of cost, availability and reliability. In the next paper a comparison of natural gas steam reforming and ethanol steam reforming for

hydrogen production will be included, considering the concept of ecological efficiency, which includes the pollutant emissions of CO_2, NO_x, SO_x and MP.

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